Measured correlation between roll-vortex signatures and radar-inferred sea surface roughness

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ABSTRACT

We present aircraft measurements of near-surface atmospheric boundary layer roll signatures and radar-derived sea surface roughness. These data are coincident in space and time. This unique feature supports attempts to quantitatively link SAR backscatter signatures to boundary layer roll impacts. The open-ocean data were collected at an altitude of 12-20 m from NOAA's Long-EZ aircraft using its turbulence probe and down-looking Ka-band radar scatterometer. We find marked correlation between measured fluctuations in the along-wind component of the horizontal wind velocity and radar backscatter for the spatial scale of 1 to 1.5 km. Close agreement between normalized modulation amplitudes suggests the surface slope variance is changing linearly with wind speed. These data were collected within thirty minutes of a RADARSAT SAR overpass where apparent boundary layer impacts of the same orientation, spatial dimensions, and amplitude are prevalent in the SAR backscatter image.

INTRODUCTION

There is ample evidence to suggest that the satellite SAR can provide high-resolution snapshots of meso- and micromesoscale atmospheric impacts on the ocean surface. Numerous reports have documented qualitative examples of such events as rain cells, storm fronts, Lee waves, atmospheric gravity waves, free convection and boundary layer rolls. Such imagery is possible because of SAR spatial resolution (typically 10 to 50 m), all-weather penetration, and sensitivity to changes in short ocean wavelets due to near-surface wind stress.

This paper presents some new information on radar ocean backscatter due to widespread atmospheric boundary layer rolls. Such events are often seen in SAR imagery and have been analyzed in the past [1,2,3] and have provided indirect confirmation of the interrelationship between 3-D helical roll vortices, their near-surface impacts, and quasi-periodicity in SAR image intensity. A new approach to study this air-sea interaction was executed using NOAA's Long-EZ aircraft to collect data during an overpass of the Canadian Space Agency's RADARSAT SAR. The experiment took place off the east coast of the United States near Cape Hatteras, North Carolina in 1997 as part of a pilot experiment for the Office of Naval Research's Shoaling Waves Research Program. Simultaneous aircraft measurements of atmospheric turbulent fluxes, radar ocean backscatter, and laser-derived sea surface slope with a finest along-track spatial scale of 1 m.

RADARSAT SAR, aircraft atmospheric and aircraft oceanic measurements will be presented here. While the SAR image was collected in an effective 'instant', it is clear that the aircraft observations over our 1-2 hour collection period were quite consistent with the satellite data.

AIRCRAFT AND SAR OBSERVATIONS

All data were acquired on 5 November 1997. The RADARSAT SAR image was acquired at 1110 UTC. This image can be seen in [4] and covers a 100 km^2 region off the North Carolina coast. Long-EZ aircraft data were gathered about the SAR scene from 1132 to 1225 UTC. Flight altitude varied from 12 to 20 m and the ground speed was 50 m/s. Our nominal 30 km flight segment was collected in about 10 minutes. Flight legs 1, 3 and 5 were flown perpendicular to the mean wind direction (40° from N) and legs 2 and 4 were flown along the mean wind.

Composite aircraft and in situ data indicated the surface conditions as follows. Near-surface wind speed was 8-9 m/s from the NE and had been so for more than six hours. The air-sea temperature difference was – 6.0° C. Boundary layer height was 1.1 km. The surface wave field was dominated by a NE wind sea with a length 50 m and significant wave height of 1.8 m. Unstable thermal conditions at the air-sea interface and a substantial wind shear at the top of the layer are both known factors associated with roll vortice development.

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As mentioned in [4], the RADARSAT image clearly shows streaking of the scale (1-2 km) and N-to-S orientation consistent with boundary layer rolls vortices. Fig. 1 presents a segment of data taken from the SAR image at a location coinciding with the aircraft's crosswind flight segments. This figure shows the SAR-derived wind speed as computed from the calibrated Standard-mode scene (wind speed algorithm of D. Thompson, JHU/APL). Data show a mean value of 9 m/s with significant signal modulation. The quasi-periodic fluctuations have a dominant length scale of 1.5 km. The rms deviation is +- 9% for this data segment corresponding to +- .7 m/s.

Simultaneous atmospheric and sea surface roughness measurements were collected within the SAR scene using the NOAA Long-EZ research aircraft. This aircraft is equipped to characterize air-sea fluxes and gas exchange. Key sensors for this study are the integrated atmospheric turbulence probe located on the aircraft's nose, three down-looking laser altimeters, and a radar scatterometer. The laser altimeters are used to measure the sea surface wave profile and to obtain an estimate of the two-dimensional surface slope for intermediate-to-long scale gravity waves. The radar is a down-looking scatterometer transmitting at Ka-band. This measurement is similar to that for altimeter backscatter. The common quasi-specular scattering assumed for the nadir viewing angles simply states that the surface slope variance is inversely proportional to the radar backscatter (with a scalar adjustment by an effective Fresnel coefficient). This measurement does differ from the Bragg-type scatter of moderate angle scatterometery but is quite intimately linked to the 20-30° viewing angles of the RADARSAT and ERS-1. These sensors are sampled at 50 Hz translating to a data point every 1 m along the flight path. Spatial resolution of the laser slope and radar measurements is 1 m.

Example aircraft wind and wave measurements are provided in Fig. 2 for the crosswind flight direction case of Leg 3. This leg was near the SAR data of Fig. 1 but occurred approximately one hour after the SAR pass. The presented flight segment is 16 km in length and was collected in five minutes. Data are derived from the raw 50 Hz (1 m) measurements using a running spatial average of 300 m to remove shorter-scale fluctuations that may be of either oceanic or atmospheric origin. The parameters shown in the top two panels of Fig. 2 are the along (U_x) and crosswind (U_y) horizontal wind velocities. It is evident that the mean wind vector is quite constant over the segment. But it is also quite clear that the data exhibit periodic modulation with length scales easily greater than 500 m. Spectral analysis indicates the dominant length scale in these fluctuations is 1.5-1.6 km. Amplitude of the crosswind modulation is slightly greater than for the alongwind. Both are of the order of .5-1.0 m/s peak to peak. Similar results were obtained for the other two crosswind legs. These results, measured well within the constant flux layer, strongly suggest a coherent secondary flow is modulating the mean. The classic crosswind 2-D roll model suggests that fluctuation in the horizontal wind velocity components should be 90 deg. out of phase and that regions of increase in the along-wind component correspond to downdrafts. Preliminary analysis of the velocity components measured by the Long-EZ appears to provide a fairly consistent rendering of such a model

The third panel in Fig. 2 represents the total sea surface slope variance, $\langle s^2 \rangle$, as inferred from the aircraft's Ka-band scatterometer. The mean value of 0.038 translates to about an 8 m/s wind speed using the Cox and Munk model [5]. Again a fluctuating component is visible across the length of the flight leg. The computed length scale for these modulations is 1.5 km. Thus the near-surface wind, the radar-inferred slope and the SAR all provide similar observations.

The simultaneous aircraft radar and alongwind (U_x) wind component measurements are compared in the final panel in Fig. 2. where fluctuations of Ux and $\langle s^2 \rangle$ are computed in percent. On each of our flight legs we see a notable agreement between the fluctuations apparent in these two signals. The correlation coefficient R between $\langle s^2 \rangle$ and U_x is 0.53. There was no measurable correlation between the large-scale surface (radar) fluctuations and the crosswind or vertical wind components. The data strongly suggest that as the near-surface alongwind component is modified by the secondary flow, these modulations directly impact small-scale surface wave roughness. The wind direction changes associated with the roll vortice crosswind component (U_y) are of the order of 10-15 deg. rms. These changes do not appear to be large enough to generate a measurable change in the surface roughness.

CONCLUSION

These aircraft data provide direct indication that measured 1.5 km modulations in near-surface wind speed due to boundary layer roll vortices also show up on the sea surface as 1.5 km-scale fluctuations in sea surface roughness. The results support previous SAR studies based on indirect methods. Further analysis of these air-sea observations is in progress.

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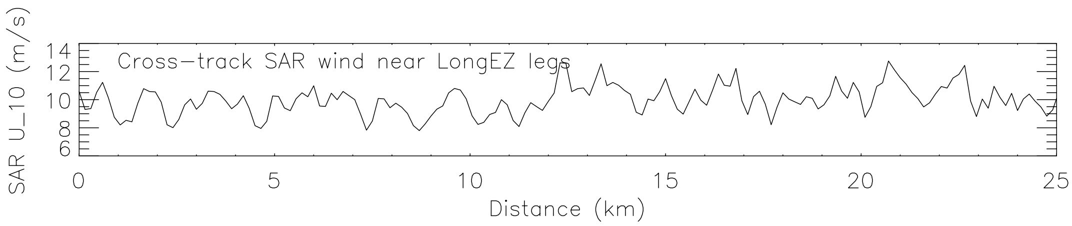

Figure 1 Variation of RADARSAT SAR 10 m wind speed along a crosswind data segment in the region of aircraft data collection.

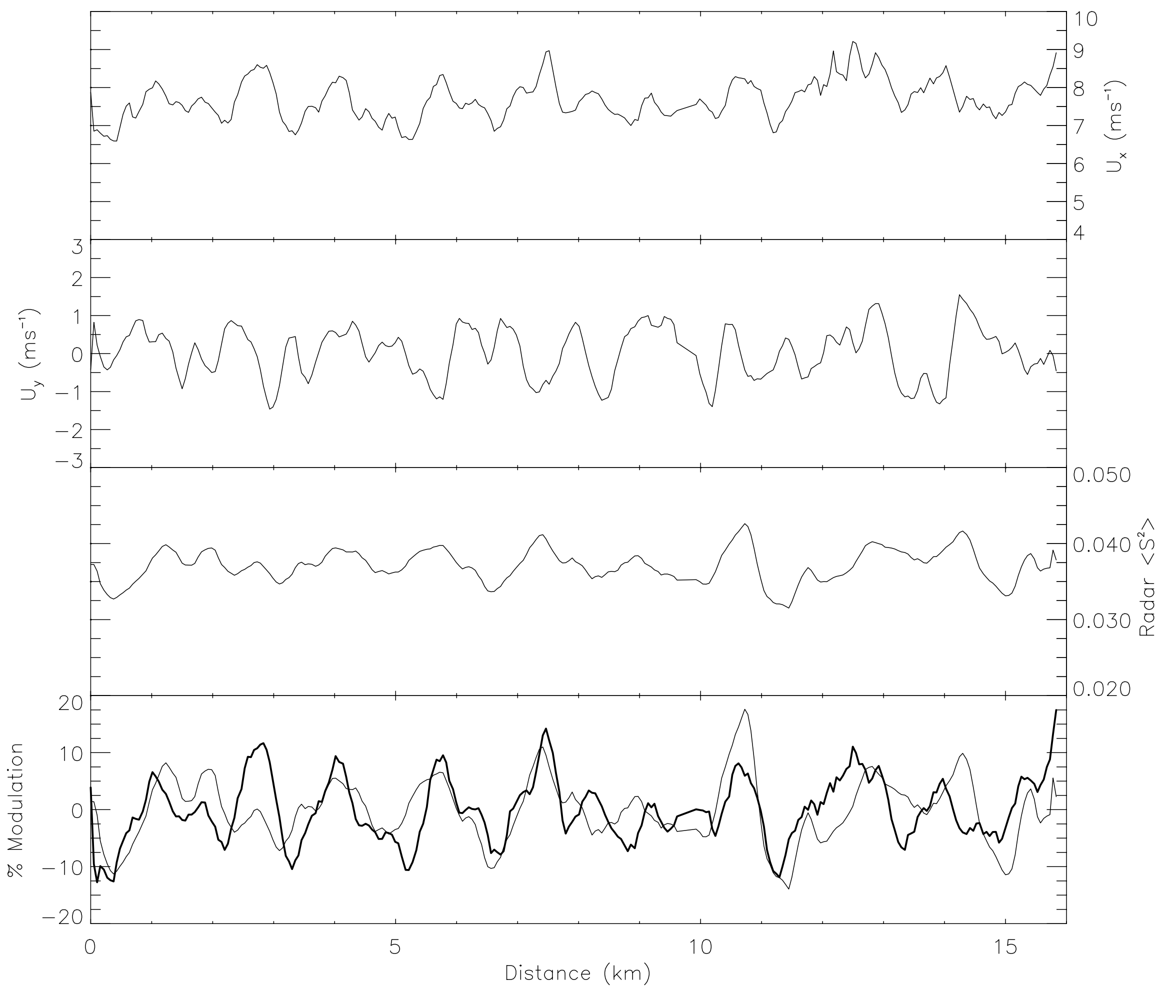

Figure 2 Long-EZ observations on a 16 km crosswind flight leg - 1204 UTC. Top two panels are along and crosswind velocities. Next panel down is the radar-inferred slope variance $<s^2>$. The final panel are the fluctuations in the alongwind velocity U_x (dark trace) and the radar slope variance.